Trend Analysis of Ground Level Ozone in the Greater Vancouver/ Fraser Valley Area of British Columbia

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[Editor's note: This is an extended abstract. The full paper was published in *Atmospheric Environment,* 37(16): 2159-2171.]

Abstract
A multiple regression model incorporating meteorological parameters, annual cycles and random error due to serial correlation was used to investigate the 1985-2000 long-term ozone trend, both year round and during the summer (May-September), at five stations in the Greater Vancouver/Fraser Valley (GVRD/FV) area of southern British Columbia. The study indicated that although average daily maximum ozone concentrations were relatively low compared to many urban areas of Canada, maximum levels, which typically occur during the summer, were similar to those measured in large urban centers in the Great Lakes-St. Lawrence corridor of southeastern Canada. Ozone levels were found to occasionally exceed the National Ambient Air Quality Objective, although these occurrences were relatively infrequent. The annual cycle of ozone was typical of areas influenced by both background and locally produced ozone, as indicated by the spring peak followed by elevated maxima occurring during summer months. Trend analysis performed on the meteorologically adjusted data found decreasing trends for summer ozone at all stations. Decreasing trends were also found for year round ozone for stations in the eastern portion of the study area, which are more greatly affected by locally produced ozone. These trends were consistent with local declines in ozone precursors and are in agreement with reported declines in summer ozone in urban areas of United States and Europe. In contrast, increasing trends were found for year round ozone at stations in the western portion of the study area, which, due to their geographical location, are less affected by locally produced ozone. There is some indication that increasing trends at sites in the western portion of the study area may be reflective of a global increase in background ozone levels. The results of this study suggest that ozone trends in the GVRD/Fraser Valley are in line with broad changes in ozone occurring in North America and Europe.

Introduction
Meteorology has been shown to play a large role in ozone formation and transport (Laurila and Latilla, 1994; Laurila, 1999; Thompson et al. 2001). In this respect, variations in meteorological conditions at different time scales can exert sufficiently large impacts on ozone concentrations that they may mask any long-term trends that could be traced to reductions in precursor emissions such as NOx and VOCs. Meteorological conditions influence ozone by affecting biogenic emissions of hydrocarbons, the atmospheric circulation and the photochemical environment (Porter et al. 2001). Studies have shown that temperature tends to be correlated with ozone concentration on a day to day basis. Higher temperatures increase reaction rates, enhance biogenic hydrocarbon emissions and increase the abundance of NOx by thermal decomposition of peroxyacetyl nitrate (PAN) (Olszyna et al. 1997). Elevated temperatures also tend to be driven by high solar radiation and are often associated with stagnant conditions which are conducive to ozone production.

The meteorological adjustment of tropospheric ozone can be achieved by statistical modeling of the association between ozone concentration and meteorological variables. Varying methods have been employed for this purpose with no single approach considered uniformly as being most appropriate (Thompson et al. 2001). Among these methods are three basic approaches: (1) selecting a robust ozone indicator that is less sensitive to variations in meteorology; (2) classifying ozone measurements by meteorological conditions; and (3) regression modeling of ozone measurements as a function of meteorological conditions. The choice of approach is generally dictated by the objective of the study, whether it be obtaining air quality forecasts, estimating trends over time or increasing the scientific understanding of the underlying mechanisms. For the purpose of trend estimation, regression modeling has been widely used to model ozone as a function of meteorological parameters, and it demonstrates the capability of detecting ozone trends disguised by meteorological variations (NRC, 1991; Rao and Zurbenko, 1994). Regression models can have varying degrees of complexity ranging from simple linear regression to more sophisticated methods incorporating temporal cycles, seasonal and meteorological factors, effects due to dependencies between consecutive measurements (serial correlation), effects due to spatial dependencies and the inclusion of intervention terms to account for relatively abrupt step changes in ozone and ozone precursor concentrations (Stoeckenius et al. 1994).

Figure 1. Map of the Greater Vancouver/Fraser Valley area showing the location of air quality (circles) and meteorological stations (squares).

In this paper a multiple regression model incorporating meteorological parameters, temporal cycles and random error due to serial correlation is used to investigate the long-term ozone trend, both annual and during the summer (May-September), at five stations in the Greater Vancouver/Fraser Valley (GVRD/FV) area of southwestern British Columbia.

Methods

Data

Five air quality sites were chosen for analysis as shown in Figure 1. Sites were chosen based on length and completeness of record and spatial coverage within the study area. Daily maximum one-hour-average ozone data were taken from the British Columbia Water Land and Air Protection Data Archive; meteorological data were taken from the Environment Canada Climatological Stations Database. Meteorological variables known to be significant predictors of the daily maximum ozone concentration in the GVRD/Fraser Valley area were chosen based on the analysis by Parker and McNeill (2002). These included: daily maximum temperature, total daily sunshine hours, mean daily wind speed and maximum daily wind speed. Table 1 identifies the locations of air quality and meteorological stations and the period of study. Although the Chilliwack station moved from one location to another in 1994, the distance between stations was approximately 1 km, and therefore it is not considered to be significant in terms of distance to emission sources.

Table 1. Location of air quality and meteorological stations and period of study.

Air Quality Stations	Period of Study	Meteorological Stations	
		Vancouver Int.	Abbotsford
Kitsilano (T2)	1987-2000	✓	
Kensington (T4)	1985-2000	✓	
Rocky Point (T9)	1985-2000	✓	
Surrey East (T15)	1985-2000		✓
Chilliwack[(a)] (T12)	1985-2000		✓

(a) Station moved from Chilliwack Works Yard to Chilliwack Airport in 1994

Trend Analysis

A geometric time variation model based on least squares fitting was applied to incorporate the effect of meteorology, temporal cycles and serial dependence:

$$C = \alpha + \beta t + \varphi\, T_{max} + \sigma S + \lambda W + \gamma \cos(2\pi t/\omega) + \delta \sin(2\pi t/\omega) + \varepsilon \qquad (1)$$

Where C is the daily maximum ozone concentration, $\alpha, \beta, \varphi, \sigma, \lambda, \gamma, \delta$, are coefficients to be determined by the regression procedure, t is the time in days, T_{max} is maximum daily temperature, S is total daily hours of sunshine, W is either the daily average or maximum wind speed, ω are cycles of various time periods, in days, and ε is the random error term that follows an ARMA (p,q) process. The term β therefore represents the slope of the long term trend after adjustment for meteorological factors and for cycles of various time periods.

The model was fitted using the general least-squares (GLS) technique in S+ (Pinheiro and Bates 2000). GLS regression uses the method of least squares to fit a continuous, univariate response as a linear function of several predictor variables using maximum likelihood, while allowing for errors to be correlated and/or have unequal variances. Various combinations of predictors including meteorological variables and temporal cycles were tested using GLS analysis to determine the most appropriate form of the model. The best model configuration was selected by means of the Bayesian Information Criterion (BIC) (Schwartz, 1978). Results were deemed to be statistically significant at $p<0.05$. Statistical analysis was performed using Statistica 6.0 (Statsoft, Tulsa, Oklahoma) and S+ 6.1 (Insightful, Seattle, Washington). Additional details on statistical methods are found in Vingarzan and Taylor, 2003.

Results and Discussion

The range of average daily maximum annual (26-33 ppb) and summer (32-40 ppb) ozone concentrations (Table 2) in the present study were typical of levels measured at background sites in Canada (CEPA 1999). In contrast, maximum summertime ozone concentrations at the four most easterly stations analyzed in this study (105-162 ppb) were similar to the range of summer daily maxima measured in large Canadian urban centers such as Toronto and Montreal (CEPA 1999). In spite of the relatively high summer maxima detected in the GVRD/FV region, ozone episodes occur relatively infrequently compared to cities in the Great Lakes/St. Lawrence River Valley area of southeastern Canada. This is reflected in the fact that exceedences of the National Ambient Air Quality Objective of 82 ppb occurred only in the 99th percentile of the summer dataset.

Table 2. Statistical summary for annual and summer (May to September) one hour daily maximum ozone concentrations (ppb) at GVRD/Fraser Valley stations for the period 1985-2000.

	Kitsilano annual	Kensington annual	Rocky Point annual	Surrey East annual	Chilliwack annual	Kitsilano summer	Kensington summer	Rocky Point summer	Surrey East summer	Chilliwack summer
No of obs.	4878	5568	5606	5589	5321	2401	2355	2351	2355	2217
Mean	26	26	29	33	31	33	32	37	40	39
Median	28	26	28	33	31	32	31	34	38	37
Min	0	0	0	0.5	0	0	4	0	8	0
Max	88	105	149	162	107	88	105	149	162	107
25th percentile	17	19	18	25	21	26	24	27	31	28
75th percentile	35	33	38	41	39	39	37	44	46	47
90th percentile	42	40	46	49	49	46	45	56	57	60
95th percentile	46	45	55	56	58	52	51	66	65	71
99th percentile	59	58	77	74	80	67	68	91	86	87
Standard dev.	13	12	16	14	15	11	11	16	14	16

Spatially, mean ozone concentrations exhibited an increasing gradient from west to east with minimum concentrations occurring at Kitsilano, the most western site, and maximum concentrations occurring at Surrey East and Chilliwack (Table 2), the two most easterly sites in the Fraser Valley. This gradient is a function of the geography of the area, which can produce high ozone concentrations during strong anticyclonic conditions that feature light winds, poor dispersion and the establishment of subsidence inversions resulting in low mixing depths. Under these conditions, which occur more frequently during the summer, the surrounding mountains act as barriers to concentrate the mix of air pollutants, resulting in a sea breeze-land breeze driven cycling of pollutants over the GVRD/FV area. This reversing flow of air effectively concentrates ozone and its precursors in the eastern portion of the area, resulting in summer ozone episodes when concentrations exceed the National Ambient Air Quality Objective.

The annual cycle was characteristic of areas affected by both background and locally produced ozone, as evidenced by the spring peak followed by elevated maxima through the summer months (Figure 2). The spring peak was the dominant feature of the annual cycle at Kitsilano, the most western site in the study area, which did not show a significant increase in concentration at the upper end of the distribution during the summer months. This is likely due to its proximity to the seashore where a frequent westerly sea breeze reduces the accumulation of locally produced ozone or its precursors. In contrast, a much reduced spring peak was observed at Chilliwack, which is located downwind from ozone precursor sources. Here, the annual cycle shows an enhanced summer peak at the upper end of the distribution. The change in the shape of the annual cycle from west to east reflects the greater importance of background conditions in the western portion of the study area and that of locally produced ozone in the eastern portion of the study area.

Contrary to the well established association between ozone and hot, sunny and stagnant conditions, ozone levels have been observed to sometimes increase with the passage of cold fronts accompanied by poor weather. Supporting this observation are reports by (Bronnimann et al. 2002) citing a negative relationship between wind speed and ozone under fair weather conditions and a positive relationship under poor weather conditions. In the current study, maximum wind speed showed a positive relationship with annual ozone, while average wind speed showed a negative relationship with summer ozone. There are several possible explanations that may account for the positive relationship between maximum wind speed and annual ozone. The first is that stratospheric intrusion tends to occur more readily during periods of atmospheric instability. Secondly, atmospheric instability is conducive to deep tropospheric mixing, which could result in regionally produced ozone being mixed down into the boundary layer. Lastly, strong winds may effectively flush out locally produced NOx that would normally act as effective ozone scavengers. In contrast, the negative relationship between average daily wind speed and summer ozone concentrations suggests that ozone levels are enhanced during stagnant conditions and reduced as wind speed increases. The different effect of wind speed on annual versus summer ozone supports the hypothesis that locally produced ozone exerts a greater influence during the summer months, while background ozone exerts a greater influence during the remainder of the year.

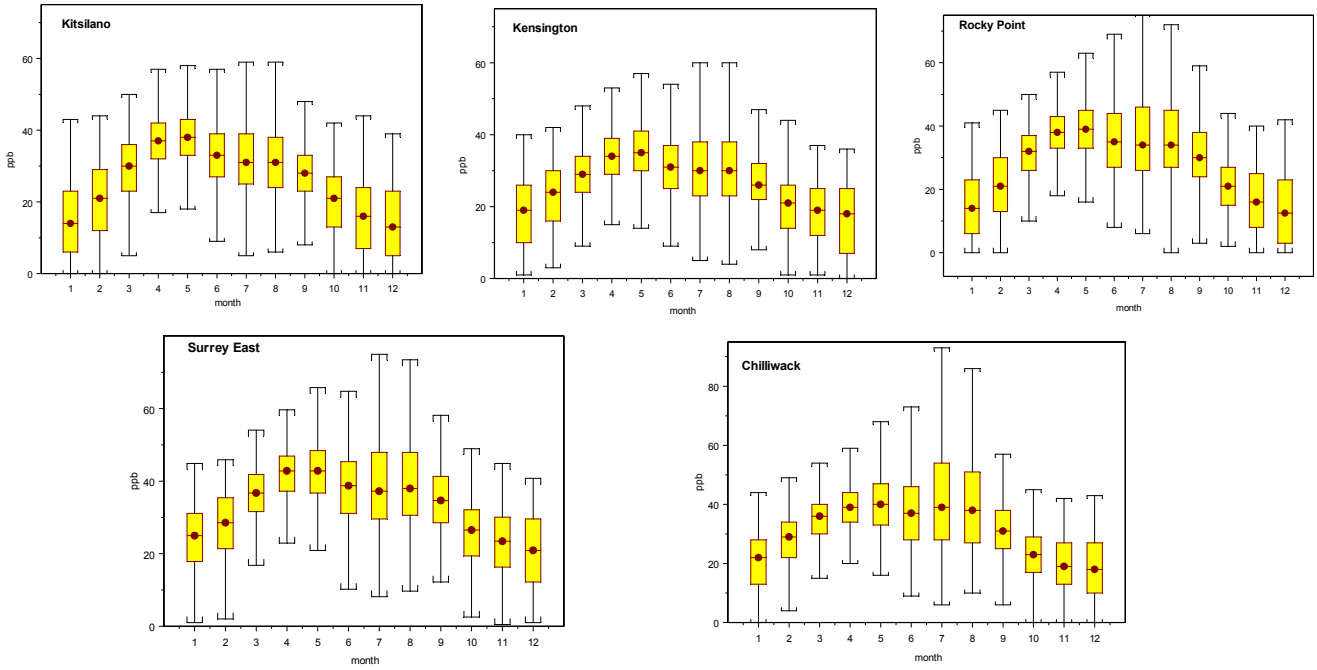

Figure 2. Seasonal cycle of the daily maximum ozone concentrations for the period 1985-2000 at the five air quality stations. Box extent indicates the 25th and 75th percentiles with the median line indicated by the circle; whiskers indicate represent minimum and maximum values except for the following: if the distance between the minimum value and the 1st quartile is more than 1.5 times the inter-quartile range (IQR), the whisker extends out to the smallest value within 1.5*IQR from the first quartile. A similar rule is used for values larger than 1.5* IQR applying to the third quartile.

The meteorologically adjusted annual ozone trend for the period 1985-2000 (Figure 3) showed spatial variability with trends increasing at Kitsilano and Kensington, in the western portion of the study area, and decreasing trends at the three stations in the east (Rocky Point, Surrey East and Chilliwack). The statistically significant declines measured at the three sites in the eastern portion of the Fraser Valley (0.19 to 0.29 ppb/yr, Vingarzan and Taylor 2003) reflect local declines in NOx and total VOC emissions during this period (GVRD/FVRD 1999; GVRD 1999). The absence of similar declines at the two most westerly stations, Kitsilano and Kensington, suggest that the latter are not as strongly influenced by locally produced ozone and may in fact be more strongly influenced by background levels which have been reported to be on the rise in both North America and Europe (Logan, 1985; Logan, 1999; Marenco et al. 1994; Simmonds et al. 1997; Lin et al. 2000, Monks, 2000). At this time, there is no overarching consensus as to why the background level is increasing. Although previous investigators have attributed this background level to natural sources (Altshuller and Lefhon, 1996), there is good evidence that it includes a major anthropogenic component associated with intercontinental transport of pollution (Marenco et al. 1994; Wang et al. 1998).

In contrast to the spatial pattern observed for annual ozone, summer ozone exhibited consistent declining trends for the 1985-2000 period at all stations (Figure 4). The greatest declines were measured at the three most easterly stations (0.64-0.94 ppb/yr, Vingarzan and Taylor 2003), reflecting their greater sensitivity to local reductions in ozone precursors. Declining trends in summertime daily maximum ozone concentrations have also been reported elsewhere. Cox (1998) reports that meteorologically adjusted daily maximum summer ozone concentrations have declined by about 1% per year in typical urban areas in the United States. Declines in summertime ozone levels in specific areas of the United States have also been reported by Lin et al. (2000; 2001), Fiore et al. (1998), Holland et al.(1999) and Wolff (2001). This decline does not appear to be restricted to North America, as similar downward trends in summer ozone from polluted air masses have also been reported Europe (Simmonds et al. 1997; Gardner and Dorling 2000). Declines in North America and Europe have been generally attributed to reductions in ozone precursors.

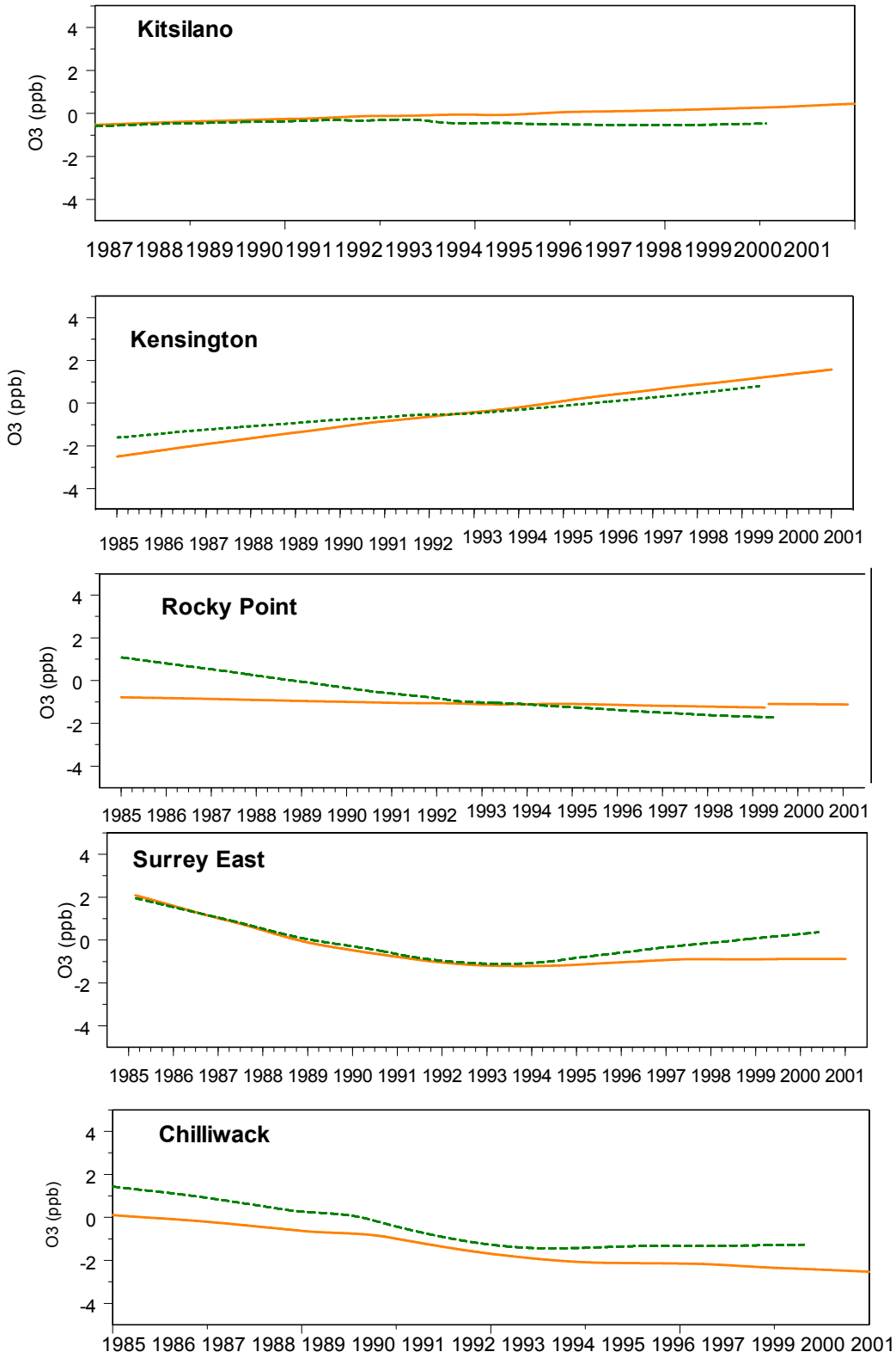

Figure 3. The long-term component of the meteorologically adjusted daily maximum annual ozone (dashed line) and unadjusted ozone (solid line) at each site. Meteorologically adjusted trend lines represent Lowess smoothed residuals from GLS regression with the trend added back; the unadjusted trend lines represent the Lowess smoothed raw ozone data centered on zero.

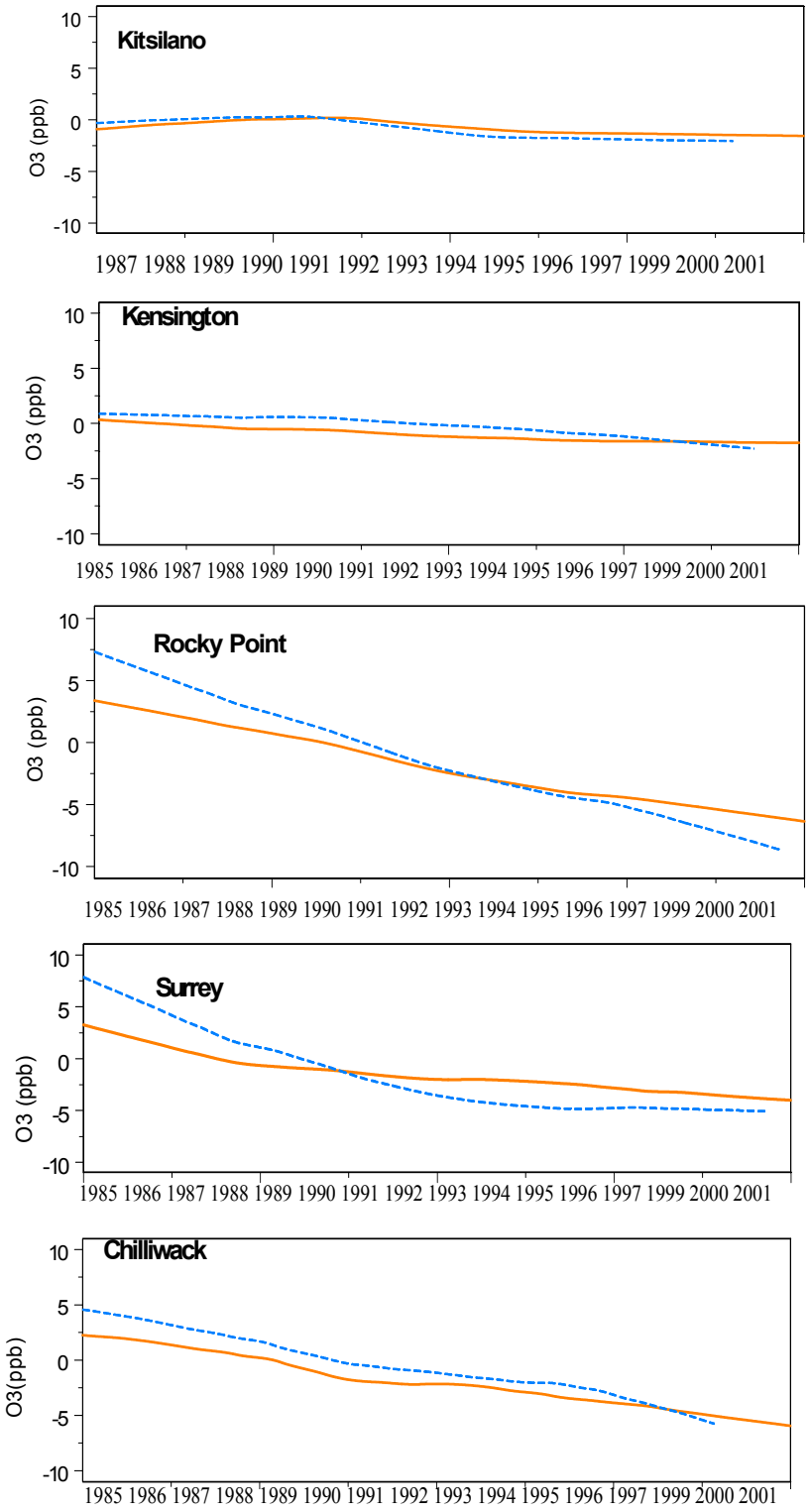

Figure 4. The long-term component of the meteorologically adjusted daily maximum summer ozone (dashed line) and the unadjusted ozone (solid line) at each site. Meteorologically adjusted trend lines represent Lowess smoothed residuals from GLS regression with the trend added back; the unadjusted trend lines represent the Lowess smoothed raw ozone data centered on zero.

Conclusions

Although average daily maximum ozone concentrations measured in the GVRD/FV area of British Columbia are relatively low compared to many urban areas of Canada, maximum levels, which typically occur during the summer, are similar to those measured in large urban centers in the Great Lakes-St. Lawrence corridor of southeastern Canada. Ozone levels occasionally exceeded the National Ambient Air Quality Objective, although these occurrences were relatively infrequent. The annual cycle of ozone was typical of areas influenced by both background and locally produced ozone, as indicated by the spring peak followed by elevated maxima during summer months. Although it is generally accepted that the spring peak is associated with the influence of background ozone, much uncertainty remains regarding the actual mechanisms responsible for its occurrence. The origin of the spring maximum in the GVRD/FV area would require further study, which would consider multiple factors including meteorology, photochemistry and long-range transport processes. Trend analysis performed on the meteorologically adjusted data found decreasing trends for summer ozone at all stations. Decreasing trends were also found for annual ozone at stations in the eastern portion of the study area, which are more greatly affected by locally produced ozone. These trends were consistent with local declines in ozone precursors and are in agreement with reported declines in summer ozone in urban areas of United States and Europe over the same period. In contrast, increasing trends were found for annual ozone at stations in the western portion of the study area, which, due to their geographical location, are less affected by locally produced ozone but are more likely to be affected by background ozone. There is some indication that increasing trends at these sites may be reflective of a hemispheric increase in background ozone levels. The results of this study suggest that ozone trends in the GVRD/Fraser Valley may be in line with broad changes in ozone occurring in North America and Europe.

Acknowledgements

The authors would like to thank Bruce Thomson of Environment Canada, Chris Houser and Dennis Fudge of the British Columbia, Ministry of Water, Lands and Air Protection and Ken Reid of the GVRD for their review of the manuscript as well as the GVRD staff for the collection of air quality data.

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